# Color Image Compression Using Demosaicing and Optimized Color Spaces

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***Abstract***

A new approach to image coding is presented. This method is based on recently introduced optimized color spaces for image demosaicing. These spaces can be used to transform the RGB color components to achieve desired properties of the new colors such as energy compactness or smoothness and thus to achieve better performance of the image reconstruction. In this work a new unified framework for color image compression is presented using demosaicing, where optimized color spaces are used both in the image coding and the demosaicing stages. A new coding algorithm based on the Discrete Wavelet Transform (DWT) is introduced and compared to presently available compression methods showing superior results both visually and quantitatively. It is concluded that the proposed unified framework and method of color space optimization are useful for storage and transmission of color images in band-limited information networks.

***Keywords***

*Color Image Compression; Optimized Color Spaces; Optimized Coding; Demosaicing; Discrete Wavelet Transform*

## Introduction

The high inter-color correlations present in most natural images (Kotera, H. and Kanamori, K. ,1990), (Limb J. O. and Rubinstein C. B., 1971), (Gershikov, E. and Porat, M., 2008) can be exploited for color image compression. Various methods have been proposed in order to reduce the amount of data that is actually coded, such as transformation ofthe RGB primaries to a new color space and then spatialtransformation ofthe new colorcomponents followed by a coding stage for them at different rates according to energy concentration or visual significance. Such a color space can be, for example, the YUV color space (Wallace, G. K., 1998), (Rabbani, M. and Joshi, R., 2002) or the KarhunenLoeve Transform (KLT) color space (Kouassi, R. K. et al., 2001). The new color components can be coded independently or using the remaining correlations (Shen, K. and Delp, E. J., 1997). Additional spatio-chromatic transforms can be applied to reduce the image data redundancy (Popovici, I. and Withers, W. D., 2005). Other approaches attempt to de-correlate the color components both spatially and chromatically at the same time (Leung, R. and Taubman, D., 2005), (Penna, B. et al., 2007) by using 3D transforming and coding, or utilize the inter-color correlations by choosing one of the components as the base and approximating the others as its function (Kotera, H. and Kanamori, K. ,1990), (Gershikov, E. et al., 2007).Here, however, we present a new image compression method based on image demosaicingas well asan efficient coding algorithm based on Rate-Distortion optimization (Gershikov, E. and Porat, M., 2007). The color processing of the proposed algorithm in the encoder and in the decoder has been optimized.

### *Image Demosaicing*

Many image acquisition devices are based on a single sensor using a color filter array (CFA), thus only partially sampled versions of the primary colors R, G, B are recorded. This is done in most cases according to the Bayer pattern (Bayer, B. E., 1976), as shown in Fig. 1. In this case, the green has twice as much samples as the red and the blue, making the green interpolation easier to be accomplished due to reduced potential of aliasing (Gunturk, B. et al., 2008). Then the red and the blue components can be reconstructed based on inter-color correlations which are usually high in natural images (Yamaguchi, H., 1984), (Roterman, Y. and Porat, M., 2007).Straightforward algorithms for demosaicing, such as bilinear or bicubic interpolation methods, however, do not use these inter-color correlations and operate on each color component independently. Better performance is achieved by algorithms that are based on the sequential scenario of the reconstruction of G first, followed by the reconstruction of R and B, e.g., (Hamilton, J. F. and

Adams, J. E., 1997), (Gunturk, B. K. et al., 2002), (Zhang, L. and Wu, X., 2005), (Chung, K.-H. and Chan, Y.-H., 2006), (Paliy, D. et al., 2007) and (Sher R. and Porat M., 2007). In such algorithms, the inter-color correlations are usually exploited by interpolating the differences $R-G$ and $B-G$.

However, since no optimization is performed, it can be shown that using these differences is not the best method to perform the task efficiently. It is better to do the image interpolation in optimized color spaces (Gershikov, E. and Porat, M., 2009). Such a color space can be, for example, the one where the High Pass (HP) energy of the color components is minimized as described in the next subsection.

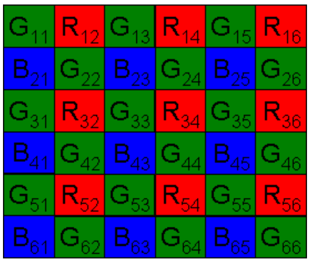



FIG. 1 THE BAYER CFA PATTERN

For the sake of completeness, it should be added that lots of effort has beenput into demosaicing research in recent years resulting in new techniques that are introduced every year. Non-sequential demosaicing methods have also been proposed, e.g. the iterative techniques of (Kimmel, R., 1999) or (Li., X., 2005) as well as vector CFA demosaicing (Gupta, M. R. and Chen, T., 2001). Most recent works can be found, for example, in (Fang, L. et al., 2012) and (Hu, C. et al., 2012).

### *Minimal HP Energy Color Space*

A general color space for demosaicing after full reconstruction of the Green component can be written as the following relation between the new color components $C_1$, $C_2$, $C_3$ and the RGB primaries:

$$(1)\; C_1 = G, \quad C_2 = a_1 R + a_2 G, \quad C_3 = d_1 B + d_2 G.$$

The optimal coefficients $a_1$ $a_2$ $d_1$ and $d_2$ can be calculated based on different optimization criteria. For example, they can be found by minimizing the HP energy of $C_2$ and $C_3$, that is

$$\sum_i \sum_j \left(C_k^{HP_x}\right)_{ij}^2 + \sum_i \sum_j \left(C_k^{HP_y}\right)_{ij}^2, k = 2,3,$$

where $\left(C_k^{HP_x}\right)_{ij}$ is $C_k$ filtered by a horizontal high passfilter $HP_x$ at pixel $(i, j)$ of the image and similarly $C_k^{HP_y}$ is $C_k$ filtered by a vertical high pass filter $HP_y$ .Minimizing the component high pass energy results in higher smoothness of the image in the new color space and thus betterperformance of the demosaicing techniques is achieved. In fact the minimal HP color space is superior to other choices (Gershikov, E. and Porat, M., 2009). The optimal $a_1, a_2$ coefficients for this problem are

$$(2)\; a_1 = \frac{\alpha_{12} + \alpha_{22}}{\alpha_{11} + 2\alpha_{12} + \alpha_{22}}, \quad a_2 = -\frac{\alpha_{12} + \alpha_{11}}{\alpha_{11} + 2\alpha_{12} + \alpha_{22}},$$

where $\alpha_{11}$, $\alpha_{12}$ and $\alpha_{22}$ are calculated by applying the HP filters to R and G:

(3)

$$\alpha_{11} \triangleq \sum_i \sum_j \left[\left(R^{HP_x}\right)_{ij}^2 + \left(R^{HP_y}\right)_{ij}^2\right],$$

$$\alpha_{22} \triangleq \sum_i \sum_j \left[\left(G^{HP_x}\right)_{ij}^2 + \left(G^{HP_y}\right)_{ij}^2\right] \text{ and}$$

$$\alpha_{12} \triangleq \sum_i \sum_j \left[\left(R^{HP_x}\right)_{ij}\left(G^{HP_x}\right)_{ij} + \left(R^{HP_y}\right)_{ij}\left(G^{HP_y}\right)_{ij}\right].$$

The solution to the $d_1$ and $d_2$ coefficients is the same as the solutionto $a_1$ and $a_2$, respectively, in (2) with B replacing R everywhere in (3). In this work $HP_x$ is the Sobel gradient filter given by

$$HP_x = \begin{pmatrix} 1 & 0 & -1 \\ 2 & 0 & -2 \\ 1 & 0 & -1 \end{pmatrix} \text{and } HP_y = \left(HP_x\right)^T.$$

The structure of this work is as follows. The color image coding framework based on demosaicing is presented in the next section, where the stages of a compression algorithm based on it are discussed in detail as well. Simulation results for the proposed method are shown in Section "Compression Results" and compared to available methods. The last section provides summary and conclusions.

## Image Compression by Demosaicing

We present an application of an optimized demosaicing algorithm to color image coding. The idea is to create a Bayer pattern (Bayer, B. E., 1976) of a given color image and then to compress it. Coding this

single image instead of the full three color components has already reducedthe coded amount of bits significantly. The coding is performed considering the Bayer pattern (Fig. 1) as made of four components according to color: $RR$ for the red, $BB$ for the blue and $GR$ and $GB$ for the green (see Fig. 2). Each of these components is subband transformed and quantized followed by lossless post-processing. The reconstruction of the image is performed by decoding each of the four components and then running a demosaicing algorithm to reconstruct the full color image from the Bayer pattern. First the encoder and then the decoder are outlined.

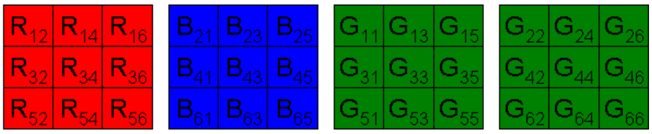



FIG. 2 THEBAYERPATTERN COMPONENTS: RR,BB, GR AND GB (FROM LEFT TO RIGHT).

### *The Encoding Algorithm*

As a first step, a Bayer pattern is created for a given image. This is done by sampling the image keeping only the pixels at the locations that are shown in Fig. 1. Then the compression method described next is applied to this pattern.

#### *1) The Compression Method*

The four channels $RR$, $BB$, $GR$ and $GB$ of the Bayer pattern (Fig. 2) are coded together using a Rate-Distortion model for subband transform coders (Gershikov, E. and Porat, M., 2007). The stages of the coding algorithm are given below.

1. Apply a color transform to the input channels to achieve better energy concentration. If we denote the channels at some pixel by $\mathbf{x} = [RRGRGBBB]^T$ and the color transform matrix by $\mathbf{M}$, then this stage is given by

$$(4)\ \tilde{\mathbf{x}} = \mathbf{Mx},$$

where $\tilde{\mathbf{x}} = [C_1C_2C_3C_4]$ is the vector of the new color components at the same pixel. The DCT can be used as (Gershikov, E. and Porat, M., 2006) a color transform for the RGB color components and thus the three color componentsare suggested to be takenwhich correspond to the application of the following DCT matrix to the $BB$, $RR$ and $GB$ channels:

$$\mathbf{M}_{\mathbf{DCT}} = \begin{pmatrix} 0.333 & 0.333 & 0.333 \\ 0.500 & 0.000 & -0.500 \\ 0.250 & -0.500 & 0.250 \end{pmatrix}.$$

Note that this DCT matrix is normalized to $L_1$ norm of 1 for each row. The fourth color component can be taken simply as $GR-GB$. The resulting $\mathbf{M}$ (normalized and applied to $\mathbf{x} = [RRGRGBBB]^T$ is thus

$$(5)\quad \mathbf{M} = \begin{pmatrix} 0.333 & 0.000 & 0.333 & 0.333 \\ 0.000 & 0.000 & -0.500 & 0.500 \\ -0.500 & 0.000 & 0.250 & 0.250 \\ 0.000 & 0.500 & -0.500 & 0.000 \end{pmatrix}.$$

2. Apply the Discrete Wavelet Transform (DWT) to each of the new color components.

3. Quantize the DWT coefficients of each color component using quantization steps derived from optimal subband rate allocation (Gershikov, E. and Porat, M., 2007). The quantization steps are part of the output bit-stream.

Use a lossless post-quantization coding technique, such as in the Embedded Zerotree Wavelet (EZW (Shapiro, J. M., 1993)) algorithm to code the quantized DWT coefficients using the intra-subband and inter-subband correlations.

### *The Decoding Algorithm*

The decoder has to decompress the four colorchannels $RR$, $BB$, $GR$ and $GB$, to arrange them in a Bayer pattern and then a demosaicing algorithm is applied to it. The decompression technique and the proposed demosaicing method are depicted in the following subsections.

#### *1) Decompression*

To decode the four color channels, the following stages are performed.

1. Inverse post-quantization coding, corresponding to the one used in Step 4 of the compression method.

2. Inverse quantization of the DWT coefficients of the four color components.

3. Inverse DWT applied to the coefficients of each of the color channels.

4. Inverse color transform, which can be

described by

$$(6)\ \hat{\mathbf{x}} = \mathbf{M}^{-1}\hat{\hat{\mathbf{x}}}$$

where $\hat{\hat{\mathbf{x}}}$ and $\hat{\mathbf{x}}$ are the vectors of the reconstructed color components before and after the inverse color transform, respectively.

### 2) Demosaicing

Once the four colorchannels $RR$, $BB$, $GR$ and $GB$ have been decoded, they are arranged into a Bayer pattern and a demosaicing algorithm is performed. In this work a basic demosaicing algorithm consisting of the following stages has been selected:

1. The green color component is interpolated using edge preserving filtering (Hamilton, J. F. and Adams, J. E., 1997). Other more complex techniques can be used here for the reconstruction of the green, such as (Zhang, L. and Wu, X., 2005).

2. The interpolated green component $\hat{G}$ is used in thereconstruction of the red and blue colors. The linear combinations

$$(7)\ C_{RG} = a_1 R + a_2 \hat{G}, \quad C_{BG} = d_1 B + d_2 \hat{G}$$

are calculated at the known pixels of the red and the blue colors,respectively. Based on the results in Ref. 9, thedemosaicing algorithm used is optimized according to the minimal HP method(see Subsection “Minimal HP Energy Color Space”),which is proved to be best there. Then the red-green combination isinterpolated at the locations of the known blue samples, and theblue-green combination is interpolated at the locations of theknown red samples using a local polynomial approximation (LPA)filter (Paliy, D. et al., 2007).

3. The missing pixels in the red and blue - those at the locations ofthe known green pixels are reconstructed using bilinearinterpolation, resulting in full images $\hat{C}_{RG}$ and $\hat{C}_{BG}$ .

4. The final red and blue components are calculated according to

$$(8)\ \hat{R} = \frac{\hat{C}_{RG} - a_2\hat{G}}{a_1} \text{ and } \hat{B} = \frac{\hat{C}_{BG} - d_2\hat{G}}{d_1}.$$

The reconstructed red, green and blue components of theimage $(\hat{R}, \hat{G}, \hat{B})$ are the output of thedecoder.

***Post-processing***

The result of the demosaicing algorithm can be refined using a post-processing method (Chang, L. and Tam, Y. P., 2004). In addition to that, the compression algorithm proposed in this work often results in "salt and pepper" type of noise in the reconstructed image. Thus median filtering can be applied in the smooth areas of the image.

## Compression Results

Here the performance of the proposed coding algorithmis compared to another DWT based method - the JPEG2000 standard(Rabbani, M. and Joshi, R., 2002), (JPEG 2000 Part I, 2000). We use the common objectivemeasure of PSNR (Peak Signal to Noise Ratio):

$$(9)\qquad PSNR \triangleq 10log_{10}\frac{255^2}{MSE},$$

where $MSE$ is the mean square error between the reconstructedimage $\hat{I}$ and the original one $I$ . It is calculatedaccording to:

$$(10)\qquad MSE \triangleq \frac{1}{3}\sum_{k\in\{R,G,B\}}\sum_i\sum_j\left(I_k(i,j) - \hat{I}_k(i,j)\right)^2.$$

$I_k(i,j)$ and $\hat{I}_k(i,j)$ here are the $k^{th}$ colorcomponents of $I$ and $\hat{I}$ , respectively. The algorithms are also compared using the subjective PSPNR (Peak Signal toPerceptible Noise Ratio) measure, given by

$$(11)\qquad PSPNR \triangleq 10log_{10}\frac{255^2}{WMSE},$$

where $WMSE$ is the weighted mean square error of thereconstruction (different weights are assigned to differentfrequency bands). The results in terms of PSNR and PSPNR for thenew algorithm and JPEG2000 are summarized in Table 1 for the test images shown in Fig. 3. As it can be seen, the proposed method outperforms JPEG2000 for all the images witha gain of 1.65dB PSNR and 1.35dB PSPNR on average.

A visual comparison is given in Figs. 4 and 5. Once again the new algorithm issuperior. Note the color artifacts and blur introduced byJPEG2000, especially in the regions marked with a frame.

FIG. 3 THE COMPRESSION TEST IMAGES: LENA, PEPPERS,TREE, BABOON, FRUITS, CAT, TULIPS AND MONARCH.

TABLE 1 PSNR AND PSPNR RESULTS FOR THE NEW ALGORITHM AND JPEG2000 AT THE SAME COMPRESSION RATE FOR THE TEST IMAGES.(BPP STANDS HERE FOR BIT PER PIXEL).

| Image | PSNR [dB] | | PSPNR [dB] | | Rate[bpp] |
|---|---|---|---|---|---|
| | New Alg. | JPEG2000 | New Alg. | JPEG2000 | |
| Lena | 28.12 | 26.63 | 36.14 | 34.88 | 0.25 |
| Peppers | 27.45 | 24.36 | 35.10 | 31.96 | 0.25 |
| Tree | 25.12 | 23.12 | 33.45 | 31.78 | 0.25 |
| Baboon | 23.30 | 21.90 | 32.93 | 31.77 | 0.25 |
| Fruits | 23.09 | 21.76 | 33.06 | 31.70 | 0.25 |
| Cat | 24.03 | 22.47 | 34.14 | 33.49 | 0.25 |
| Tulips | 24.28 | 22.15 | 32.57 | 30.58 | 0.25 |
| Monarch | 24.80 | 24.63 | 33.31 | 32.88 | 0.25 |
| Mean | 25.03 | 23.38 | 33.78 | 32.43 | |

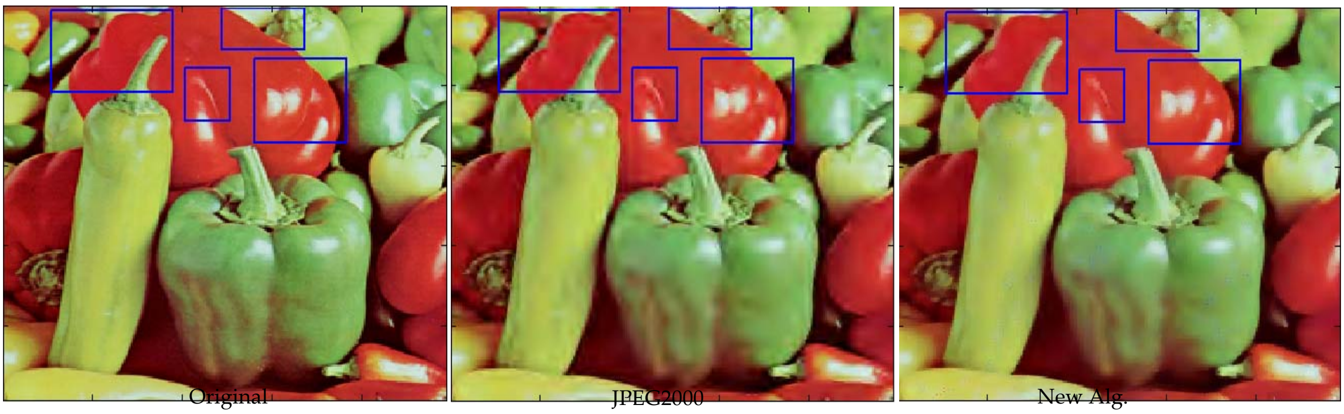
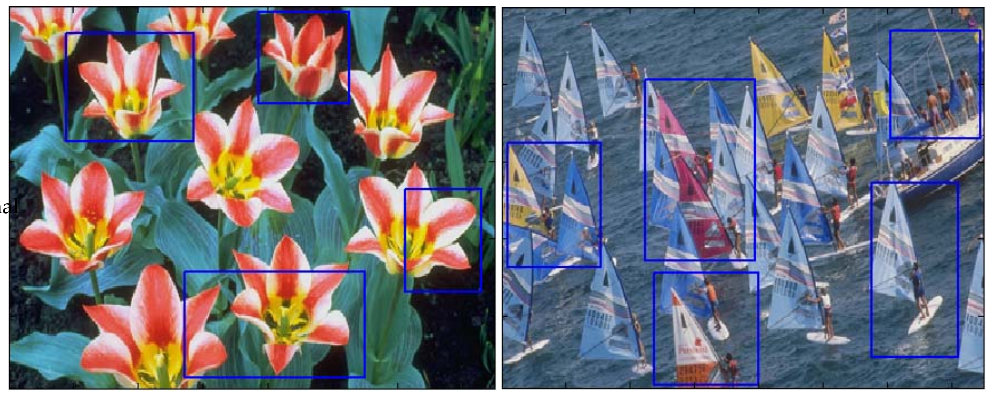



FIG. 4 COMPRESSION RESULTS FOR PEPPERS AT 0.63 BIT PER PIXEL (BPP): ORIGINAL, JPEG2000 AND THE NEW ALGORITHM.



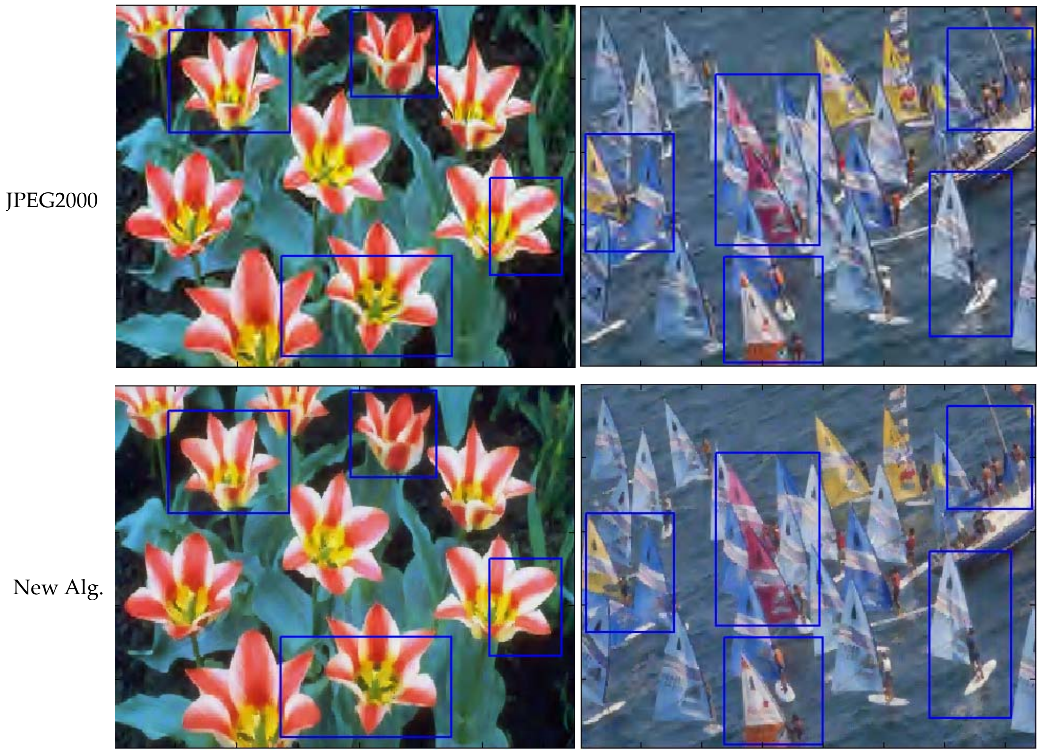



FIG. 5 COMPRESSION RESULTS FOR TULIPS AT 0.51BPP AND SAILS AT 0.37BPP (FROM TOP TO BOTTOM): ORIGINAL, JPEG2000 ANDTHE NEW ALGORITHM.

### *Summary and Conclusions*

A unified optimized framework of image compression usingdemosaicing is presented in this work. A color image is compressed by creating a Bayer pattern of it and then encoding it as four color channels following a color transform. The coding is based on a Rate-Distortion model (Gershikov, E. and Porat, M., 2007), from which optimal subband rate allocation is derived. The image is then decoded using a demosaicing algorithm operating in an optimized color space (minimal HP color space in this work). The comparison of the proposed compression algorithm to the JPEG2000 standard shows superior performance of our algorithm in terms of distortion measures aswell as visual quality. The simulations are performed at low rates too, which can be useful for transmission over slower communication channels. Our conclusion is that the proposed optimization framework for color images is useful for visual communication in band-limited information networks.

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